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Development of vegetal based thermal plasters with low environmental impact: optimization process through an integrated approach

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Abstract

The use of thermal insulating plasters represents an effective solution in energy retrofit of existing buildings. Thermal properties are usually improved through the addition on the plaster formulation of Light Weight Aggregates, as expanded polystyrene and perlite. The drawback of these thermal plasters is the higher environmental impact, especially when added to natural binders, as natural hydraulic lime.
Within a research activity a process of optimization was followed in order to get the most effective blend, applying iteratively the LCA methodology, measuring the thermal conductivity and testing the environmental impact in terms of Volatile Organic Compounds and formaldehyde emission rates.

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Keywords: Thermal insulating plasters; Energy Retrofit; Embodied Energy; VOC emissions,

1. Introduction

Energy retrofit of existing buildings is nowadays a priority. The use of thermal insulating plasters represents an

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effective solution, especially when it is necessary to improve the thermal behavior of the building envelope working on the internal side of the wall [1] [2].
The market for construction products, particularly at this time of economic crisis, requires innovative products characterized by the combination of low environmental impacts of production, high market competitiveness (in price, energy efficiency, installation features, etc.) and long expected service life. The technological envelope systems are no longer just a simple protective layer of the walls, but actively participate in the thermo-hygrometric balance, impacting also on indoor environmental quality. Industrial companies, aware of the complexity in designing and manufacturing such ambitious technological systems, started a wide research involving the Departments DENERG and DAD of the Politecnico di Torino, to support the design process of new thermal plasters, characterised by high thermal performance and low environmental impact [3]. The need to analyse all stages of the life cycle since the selection of raw materials, has provided the opportunity to apply an integrated and synergistic approach to the research and industrial design, in which the know-how on energy performance, environmental and technological issues, were crossed with the specific experiences in the field of industrial production of plasters[4-5]. It was then progressively developed an iterative process consisting into design, formulation, analysis and implementation, through which the materials and the prototypes were subjected to an iterative assessment process that would provide feed-back adequate to implement the prototypes, up to the creation of marketable products. The ability to operate synergistically since the selection of raw materials, producing formulations with waste materials derived from industrial and agricultural local processes (corn cob granular cork from recycled bottle caps, straw fibres), triggered a typical process of Circular Economy[6]. This approach, in which different actors derive mutual benefits from sharing waste materials, requires a systemic innovation focused on turning waste from one industry into useful materials for another one. The close synergy developed around the iterative and innovative process has led to the involved companies a threefold result: the creation of new highly competitive prototypes, a deep analysis and control of production processes and the growth of know-how on the energy and environmental performance related to the selection of raw materials. The comparison among prototypes and products already existing in the market, was necessary to establish the performance to reach or to exceed.

2. The tested thermal insulating plasters

Within the research activity four vegetal based prototypes illustrated in table 1were developed (Cork_001, BIOART CORK, VGT_001 and VGT_014) and compared with two commercial plasters, used as benchmark.

Table 1. Samples description

Plaster name	Description
Thermointonaco	Natural hydraulic lime (NHL), Portland cement, EPS, additives
Thermocalce	NHL, Portland cement, expanded perlite, additives
Cork_001	NHL, granular corncob, expanded perlite, zeolite, additives
Bioart cork	NHL, wheat straw granulated, cork granulated from bottle caps, cellulose flakes
VGT_001	NHL, zeolite, Expanded vermiculite, expanded perlite, corncob granulated
VGT0_14	NHL, Portland cement, cement sulfoalluminate (S-AL), expanded perlite, corncob granulated, wheat straw granulated

3. Experimental characterization and LCA assessment

An experimental characterization concerning thermal properties, VOCs and formaldehyde emissions was performed. Thermal conductivity under different boundary conditions was measured in order to test the effectiveness of the plasters and the degree of variability when exposed to different ambient temperatures.

Moreover, in order to take into account te indoor air quality aspects, a series of measurements using a emission test cell were performed. In figure 1 the tested samples and the lab measurements are shown.

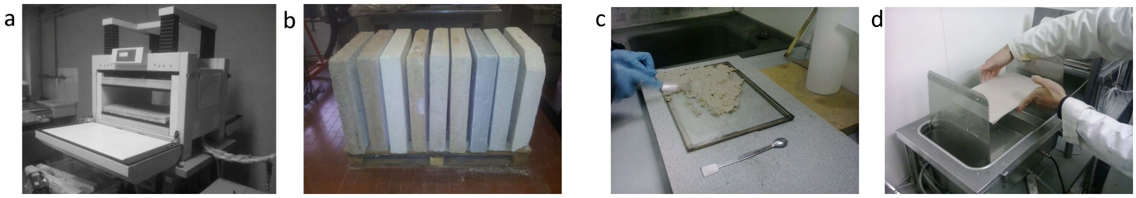


Fig. 1. (a) guarded heat flow meter; (b) plaster samples; (c) test samples preparation; (d) test samples introduction in the emission test cell.

The LCA methodology was applied in order to evaluate the environmental impacts of each plaster blend as well to assess and optimize every manufacturing process and to formulate a final product that follows proper eco-design criteria in term of energy, environmental impacts and costs.

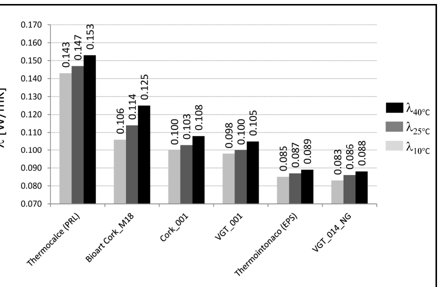
3.1. Thermal properties assessment

A set of experimental measurements were contemporarily carried out with a guarded heat flow meter apparatus (GHFM), according to international standards EN 12667:2001 [7] and ASTM518 [8], to measure the equivalent thermal conductivity for the different vegetal plaster blends. A Lasercomp FOX600 (Fig.1a), consisting of a single sample, (GHFM), was used. Laboratory measurements were performed on 6 different plaster samples (Fig.1b). Before each test all the specimens were dried to constant mass in a ventilated oven for non-less than 48 hours at 60°C. To avoid any additional surface resistances, due to the sample discontinuity and prevent damages on the (GHFM) device all the specimens were sandwiched between two rubber sheets with a thermal conductivity of 0.136 W/(mK) and 2 mm thick each.

Results are reported in table 2, where: ρ represent the sample density, d the sample thickness and $\lambda_{10°C}$, $\lambda_{25°C}$ and $\lambda_{40°C}$ represent respectively the thermal conductivity at the tree different tested temperatures (15, 25 and 40°C). Results were compared with the ones obtained for conventional thermal plasters, embedding perlite and expanded polystyrene, in order to assess the real effectiveness of the developed vegetal based plasters.

Table 2. Samples specifications and guarded heat flow meter results.

Sample name	ρ (*kg/m³*)	d (*mm*)	$\lambda_{40°C}$ (*W/mK*)	λ_{25} (*W/mK*)	λ_{10} (*W/mK*)
Thermointonaco (EPS)	278	104	0.089	0.087	0.085
Thermocalce (PRL)	361	103	0.153	0.147	0.143
Cork_001	508	101	0.109	0.103	0.100
Bioart Cork_M18	459	102	0.125	0.114	0.106
VGT_001	496	100	0.105	0.100	0.098
VGT_014	400	52	0.088	0.086	0.083



Vegetal based thermal plasters (VGT and Cork) present a thermal conductivity comparable with the non-vegetal based plasters, i.e. Thermointonaco (EPS) and Thermocalce (PRL). It is to underline that the VGT_014 presents thermal conductivity values lower than Cork_001 (around 17%) and almost the same value if compared with Thermointonaco (EPS). Nevertheless the lowest thermal conductivity results of the VGT_014 is due to the increase of perlite aggregates that gives also a strong contribute on reducing the samples density.

3.2. The LCA analysis

The environmental impacts have been evaluated with the Life Cycle Assessment methodology defined by the UNI EN ISO 14040/44 [9]. The LCA method is been applied as a tool for integrating environmental criteria into the company strategic plans. In particularly, the analysis aims to develop and improve a range of experimental prototypes of thermal plaster using natural matter as a primary source including minerals and plants, often derived from agriculture by-products or scraps. The LCA study has been developed by three progressive steps: the first one is the analysis of raw materials in order to support the formulation phase, the second one is the comparison between the prototypes and the benchmark, and the third one is the evaluation of all embodied energy of thermal plasters considering also the effect of the installation phase. The Functional Unit for the former two steps is the kWh/kg, while the functional unit of last analysis is kWh/m^2 related to a 4 cm of thermal plaster thickness.

The system boundary, covering cradle-to-gate, include all the processes from the extraction of raw materials, transports, up to the plant processes of manufacturing and packaging. The Life Cycle Inventory is based on two kinds of data: indirect and direct data. The former belongs to the database Eco-Invent v.2.0 (raw materials: lime, perlite, zeolite, vermiculite, cements, EPS). The latter have been gathered directly from companies involved in the research project. It includes processes related to: raw materials such as corncob tillage and recycled cork, transport route, the transformation of wheat straw granulated, corncob granulated, cork granulated, and the plant's processes related to experimental thermal plasters manufacturing.

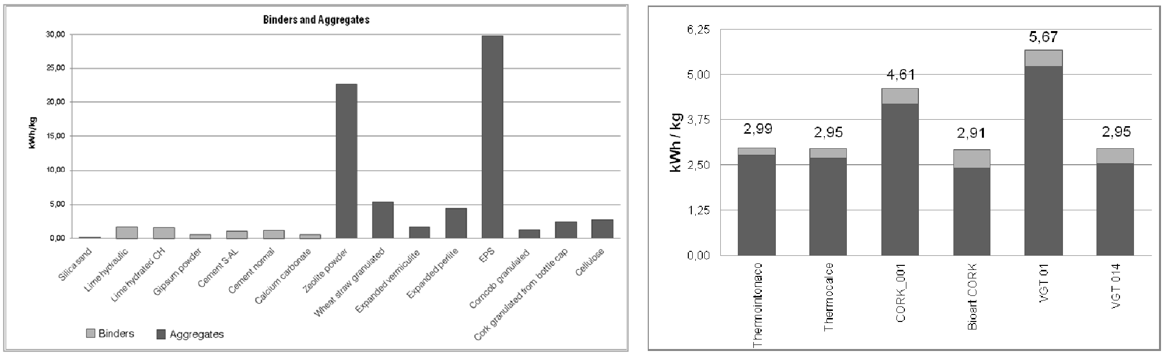


Fig. 2. (a) Embodied energy of raw materials; (b) Embodied energy of 1 kg of thermal plasters.

The comparison between binders and aggregates based on the adaptation of data from Ecoinvent (excluding wheat straw and granular corn cob, whose are direct data), underlines the need to maximize the use of vegetal materials waste, trying to contain mainly the amount of zeolites. However, EPS, despite its low ecological features, gives excellent performance in thermal resistance in relation to the minimum amount by weight in the mixture (Fig.2). The environmental and energy analysis of materials were fundamental in a blend formulations for a thermal plaster prototypes. The usefulness of the raw materials analysis is demonstrated in the comparison study of mixtures: the VGT 001 is in fact much more impactful of VGT 014, since, in the last formula the zeolite was removed (Fig.2b). Results of the LCA analysis are shown in Fig. 3 and in table 3, where: NRE is the content of non-renewable energy, RE is the renewable energy, evaluated with the CED method v. 1.06; GWP is the global warming potential expressed in carbon dioxide equivalent, constancy with IPCC emission factors. The analysis highlights a correspondence between the GWP and the energy analysis for each product. table 3 show that the emissions related to thermointonaco (EPS), thermocalce (PRL), bioart cork and VGT_014 are comparable. The last step of the environmental impact assessment is represented by the evaluation of technological characteristics in the installation phase. Different quantities needed of each plaster, in relation to the thickness and the surface, affect the total amount of powder used: the quantity of mixture used for the Thermointonaco is 8,6 kg, about half of that of the other plasters. The fig. 3 points out that the relationship between the embodied energy of the six plasters change again, and Thermointonaco reveals to have the lower impact especially by virtue of the very low weight of the aggregate in EPS.

Sample name	NRE (kWh/kg)	RE (kWh/kg)	GWP ($kgCO_2eq/kg$)
Thermointonaco	2.75	0.23	0.854
Thermocalce	2.68	0.27	0.928
Cork_001	4.20	0.41	1.180
Bioart Cork	2.42	0.49	0.889
VGT_001	5,21	0.46	1.371
VGT_014	2.52	0.43	0.881

Table 3. LCA results CED and GWP100 IPCC

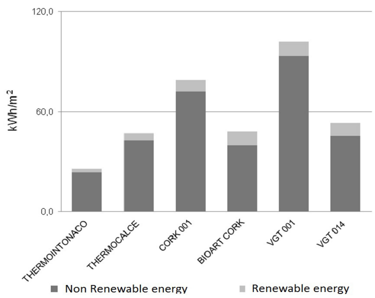


Fig 3. Embodied Energy for 1 m^2 with 4 cm of thickness

3.3. Laboratory measurement of (VOCs) and formaldehyde emission

Interior building materials can be significant pollutant emission sources and therefore can definitely affect the indoor air quality. A number of investigations on the emission from indoor sources have shown that interior architectural coatings, such as paint and varnishes, contribute to indoor air pollution, in particular during the installation process [10]. However in the literature does not appear sufficiently investigated the contribution of some products commonly used for the substrate, such as plaster, which although appear to be an integral part of the final solution. Few studies are therefore available, such as Kwok et al. (2003) [11], showing the influence of substrate on VOCs emissions from paint and varnishes and founding that VOCs emission closely related to the substrate type.

Laboratory measurements have been performed to assess the release of Volatile Organic Compounds (VOCs) and formaldehyde of some types of thermal plaster, VGT014 and BIOART CORK, in order to optimize their formulation, to assess their Indoor Air Quality (IAQ) performance, to compare different blends. Emission tests of (VOCs) were made at the Istituto Giordano (RN, Italy), accredited technical institution for the product testing and certification.

The test was carried out using testing chamber method according to standard UNI EN ISO 16000-9:2006 [12]. The products were applied on a substrate of glass, with a test specimen surface of 0,06 m² (Fig. 1c). The weight amount was respectively 240 g (VGT014) and 136 g (BIOART CORK). The test specimens were positioned in a chamber of 0,06 m³ (loading factor 1 m²/m³).

Air sampling has been done after 8 and 28 days after introduction of the test specimen in the emission test chamber (Fig. 1d), using markes sorbent tubes (carbopack C 60/80, Carbopack B 60/80, Carbosieve SIII 60/80) for VOC analysis by GC-MS and using tubes containing silica gel coated with 2,4-dinitrophenylhydrazine (DNPH) formaldehyde analysis by HPLC-UV.

Results are reported in table 4 and compared to the French classification [13], based on emission after 28 days. French regulation foresees that since 2012, any covered product placed on the market has to be labelled with emission classes based on their emissions, as tested with ISO 16000 and calculated for European reference room, needed for comparing test result with air concentration limit values. The same reference room is used in EU Countries with advanced IAQ standard and rules, as Germany and Belgium.

The comparison shows that the tested products have extremely high performances, coming in emission class A + for the French market for all parameters analyzed. The main differences are found in the emission of (TVOCs) on the third day: VGT_thermal plaster is more performant, with values more than halved compared to Cork_thermal plaster. The larger particle size of the latter, and therefore the greater surface area exposed to the air, contributes to increasing emissions in the short-term measurements (C6-C16 expressed in toluene equivalent, according to ISO 16000-6:2011).

Table 4. Test results and comparison with French classification.

Testing parameters	VGT014 Results [µg/m³]			Bioart cork Results [µg/m³]		
	8 days	28 days	Emission class	8 days	28 days	Emission class
Formaldehyde	<3	<3	A+ (<10)	<3	<3	A+ (<10)
Acetaldehyde	<3	<3	A+ (<200)	<3	<3	A+ (<200)
Toluene	<2	<2	A+ (<300)	3	<2	A+ (<300)
Tetrachloroethylene	<2	<2	A+ (<250)	<2	<2	A+ (<250)
Xylene isomers	<2	<2	A+ (<200)	4	<2	A+ (<200)
1,2,4 Trimethylbenzene	<2	<2	A+ (<1000)	<2	<2	A+ (<1000)
1,4 Dichlorobenzene	<2	<2	A+ (<60)	<2	<2	A+ (<60)
Ethylbenzene	<2	<2	A+ (<750)	<2	<2	A+ (<750)
2-Butoxyethanol	<2	<2	A+ (<1000)	<2	<2	A+ (<1000)
Styrene	<2	<2	A+ (<250)	<2	<2	A+ (<250)
TVOCs	107	<5	A+ (<1000)	258	<5	A+(<1000)

4. Conclusions

The development of new ecological thermal plasters to be used in refurbishment or in new buildings aimed at realizing high energy efficiency and high indoor air quality environments has to face different aspects. The thermal conductivity, which in the past represented the key factor in the selection of Light Weigh Aggregates, reveals to be no more the driving property when the whole energy related issues are considered and indicators concerning the environmental scale are duly taken into account. Circular economy, Embodied Energy, Global Warming Potential, along with VOC and formaldehyde emissions shall form an integral part of the development process.

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